Historic, archived document

Do not assume content reflects current scientific knowledge, policies, or practices.

A280.39
M34Am
Cop. 2

AMS-126

June 1956

U. S. DEPARTMENT OF AGRICULTURE

UNITED STATES DEPARTMENT OF AGRICULTURE
Agricultural Marketing Service
Washington, D. C.

PROGRESS REPORT ON COLOR RENDITION STUDIES

By Dorothy Nickerson, Color Technologist
Cotton Division

Chairman, Subcommittee on Color Rendition,
I.E.S. Light Sources Committee

(Paper given at Illuminating Engineering Society, Eastern Regional Meeting, May 24-25, 1956, Washington, D. C.)

"From time immemorial, man must have viewed with delight and wonderment the transparent blue of the zenith sky, the glowing scarlets and oranges of the setting sun, and the softly varied hues of that celestial harbinger of hope, the rainbow. The shimmering plumage of the peacock; the multihued corollas of the flowers; the golden browns and russets of the autumnal foliage, so contrasting with its erstwhile vernal green; the bright foreboding red of spurting blood; the flickering yellow of a tallow flame in the deep recesses of the caves, painting restless shadow-pictures on the walls--all these were but a few of the vibrant notes in the stirring color symphony of life." 1/

This opening paragraph of Chapter I of "THE SCIENCE OF COLOR," a highly technical book on the science of colorimetry, is clear indication of the natural partnership of Art, Science, and Industry if in today's world COLOR is to be understood and used with satisfaction.

In the days of firelight, or even of the candle, it seems hardly probable that much thought was given to appearance of colors under nighttime illumination. Perhaps note was made of the added sparkle of bits of glass or of polished metals under these early man-produced light sources. It was only 100 years ago that the synthetic dye industry began (this year we celebrate the Perkin Centennial, the discovery by William Henry Perkin, a young English chemist, of the first synthetic dye) and it is less than 100 years since the first commercial incandescent electric lamp was produced in 1881. Man has within himself a very remarkable and not entirely understood mechanism for detecting color, but without Perkin and the modern colorants which today are applied to all kinds of products, and without Edison and the modern light sources that provide enough light to distinguish small differences by night as well as by day, we might not find the illuminating

---

1/ From "THE SCIENCE OF COLOR," Committee on Colorimetry, Optical Society of America, Crowell (1953).

engineer so clearly faced with the necessity of studying color science, not only in regard to its esthetic use but (more in his line of thought although a lot harder to understand) along scientific and engineering lines. He is, however, an engineer and as such should no less expect to master color in a few brief, easy lessons than he would expect to understand and master the use of electricity and its part in lighting by merely sitting in on a few lectures. Color is so much a matter of everyday experience that too often the esthetic side of it is thought to be its only, or at least its most important, feature.

If all of our light sources were in the same family, so that the change from one to another would provide a regular transition in spectral distribution (as do the various colors of daylight which range from yellow sunlight to blue skylight), the illuminating engineer often could skip the tedious necessity for learning the whys of the color changes because they would be so regular that he might be satisfied to learn only the what of these changes. But our new light sources vary so much from one to another in the amounts of energy they radiate at different wave lengths that one cannot tell by looking at the source itself what its effect will be on the colors of objects seen under it.

This could be made dramatic by showing you two yellow lamps that might look alike as you look directly at them. But if one is a sodium lamp and the other is either a yellow fluorescent or a tungsten lamp seen through a yellow filter, the appearance of objects seen under these different sources would be so completely different that one need not be an expert to rate them for their relative "color rendition" properties.

But these dramatic instances are of little practical value, for except for special purposes, as in street lighting, no one uses such lamps, certainly not when they expect colors of objects to retain their daylight appearance. We do, however, use both fluorescent and incandescent lamps. And even if we restrict ourselves to consideration of fluorescent and incandescent light sources that are in the range of what are considered "white" lamps, our problem remains.

Taking note of this very practical problem, the I.E.S. Light Sources Committee at its April 17, 1952 meeting, established a subcommittee to deal with the subject of color rendition, specifically, "To establish a method of measuring and specifying the color rendition properties of light sources," it being recommended that priority be given to fluorescent lamps.

Members of the subcommittee cover a wide representation of theoretical and practical interests:

E. W. Beggs (1956, following L. Thorington), Westinghouse Electric Corp., Bloomfield, N. J.

C. N. Clark (1954, following A. C. Barr), General Electric Company, Nela Park, Cleveland, Ohio.

C. W. Jerome, Sylvania Electric Products, Inc., Salem, Mass.

D. B. Judd, National Bureau of Standards, Washington, D. C.

Norman Macbeth, Macbeth Corporation, Newburgh, N. Y.

Dorothy Nickerson, U. S. Department of Agriculture, Washington, D. C.

C. R. Stillwell, Bell Telephone Laboratories, New York, N. Y.

Carl E. Swanson (1954), Durotest Corporation, North Bergen, N. J.

Arthur W. Weeks, Champion Lamp Works, Lynn, Mass.

It would give me a great deal of satisfaction if I were able to report to you today on the completed work of this subcommittee, or failing that, if I were able to sum up in words of one syllable just what you, who have problems of lighting for color grading and inspection, or for providing a pleasant or "natural" appearance of colors, could do to provide lighting installations that would be a solution. I can do neither. As chairman of the Subcommittee on Color Rendition, I shall outline to you how we are facing the problem, and how far along we are towards providing a practical answer.

The work of the subcommittee is based on consideration of seven items presented by Dr. Deane B. Judd to the first session (September 22, 1952). These I shall present to you:

1. What is the Purpose of the Desired Method?
2. What Form Should the Results of the Method Take?
3. What Type of Test is Practical and Significant?
4. On What Basis Should the Test Objects be Chosen?
5. What Source Should be Used as a Standard Against Which to Check the Color Rendition of the Test Source?
6. If a One-Number Approximate Rating is Desired, on What Basis Should this Number be Derived?
7. What Sort of Program of Study Should be Established?

On several of these questions the subcommittee was able to reach decisions promptly, in fact, after the second meeting, surely after the third, the main line of work seemed clear and there has been agreement on our method of attack.

1. WHAT IS THE PURPOSE OF THE DESIRED METHOD?

The I.E.S. Committee on Light Sources in establishing the Subcommittee stated (minutes of April 17, 1952 meeting) that the scope should be: "To establish a method of measuring and specifying the color rendition properties of light sources," and recommended that priority be given to fluorescent

lamps. The subcommittee supports this statement of scope and accompanying recommendation, and interprets the desired method as one that should be broad enough to deal with all light sources, present and future, of whatever design, and that the method should not be restricted as to purpose. For example, it shall provide for the assessment of DeLuxe type lamps, present and future, relative to the standard types, and it shall also provide for control of lamps of the same type for interchangeability.

2. WHAT FORM SHOULD THE RESULTS OF THE METHOD TAKE?

It was decided that one of the results of the method should be a one-number approximate color-rendition rating of the light source, but that this should be supplemented by a more rigorous multi-number rating. The hope was expressed that this multi-number rating might be formulated so as to be considerably less complicated than the 35-number rating provided for fluorescent lamps by the spectroradiometric curves at intervals of 10 mμ, plus the four chief mercury lines.

3. WHAT TYPE OF TEST IS PRACTICAL AND SIGNIFICANT?

It was decided that the test should be based on test objects specified by spectral reflectance from which the colors are computed for a test source of known spectroradiometric curve in accord with an hypothetical standard observer. Actual observation of test objects illuminated by actual sources shall be used in validation of the test method, but not in the test method itself.

4. ON WHAT BASIS SHOULD TEST OBJECTS BE CHOSEN?

There was a question as to whether the test objects should be chosen: (A) to test the source in all the chief parts of the spectrum; (B) to yield colors of all hues at moderate saturation; (C) or particularly from objects (such as meat, butter, lettuce, coffee, and the human complexion), whose color rendition is of general interest.

At its first meeting the subcommittee agreed that test objects should include those whose color rendition is of considerable practical importance, and in the second subcommittee session observations were made on these objects, on several metameric pairs, and on 18 of the 20 Munsell papers that Barr, Clark, and Hessler used in studies reported to the I.E.S. Technical Session in 1952. The chief business of our second meeting was a viewing of these three classes of test objects under three light sources that were adjusted to provide the same chromaticity. This matching of the color of the three light sources was done in order to eliminate all effects that might otherwise be caused by differences in chromaticity of the light sources, and in order that subcommittee members would know that the effects they were viewing were caused by differences in spectral distributions of the sources, and not by differences in the chromaticity of those sources. The problem

of adaptation was thus ruled out of these studies in order to attack the more simple problem first. (This problem of change under different colors of light sources is included in the color rendition studies reported by Helson, Judd, and Warren in Illuminating Engineering, 51, April 1956.)

The three sources used in the subcommittee's first preliminary tests consisted of a 3000K incandescent lamp, and a Standard and a DeLuxe Warm White fluorescent lamp each of which was color-matched to the incandescent lamp. The amount of light from each source was adjusted so that it appeared equal on the duplicate sets of objects and on the gray backgrounds that were viewed. At Nela Park an exhibit was set up in two large alcoves, one provided with incandescent lamps used as a control standard, and the other provided with lamps that could be switched at will from Standard to DeLuxe fluorescent. In addition to the large alcove settings, a box was provided that permitted a single test object to be viewed simultaneously under three light sources.

The importance of this meeting in demonstrating to subcommittee members the degree and kind of color change that must be taken into consideration, even in present commercial lamps, cannot be overestimated. Before this demonstration, which lasted several hours, few of the subcommittee members were aware of the degree or kind of change that takes place under lamps of the same colors but of different spectral distributions. Nor did many of them believe that any but experts could judge the size of the color shifts with any degree of agreement. After this meeting all had seen the amount of shift, and every member of the subcommittee was convinced--in spite of former skepticism--that with a little training, and more definite instructions regarding scoring, that the subcommittee itself could agree very well among its members on a numerical scoring of lamps if it had a standard to use as 100% and one at some other stated value.

Appraisals were made at this meeting by nine persons on 29 separate object colors, and the results were statistically analyzed by Dr. Grant Wernimont at the request of Mr. Ralph M. Evans of the Color Technology Division of the Eastman Kodak Company (whose assistance in several phases of the work involving extensive computations is much appreciated by the subcommittee). It was found that when the results of the average appraisal of rendition were plotted in hue order of the samples the curve is strikingly regular, almost sinusoidal, and suggests that a suitable selection of a few samples might be adequate for testing. These results are shown in figure 1. It was found also that when the results of appraisals for the several groceries included in the test were plotted at the appropriate hue designation, the results fitted into the general curve. Mr. Barr pointed out in confirmation that in previous studies good correlation had been observed between the color changes exhibited by the Munsell papers approximating the color of test objects used and the impermanent and fast changing colors of objects whose color rendition is of commercial interest. This was fortunate, for it would be very difficult to measure and maintain a standard for a selection of groceries, or for human complexions, that could be used under lengthy or repeated observations.

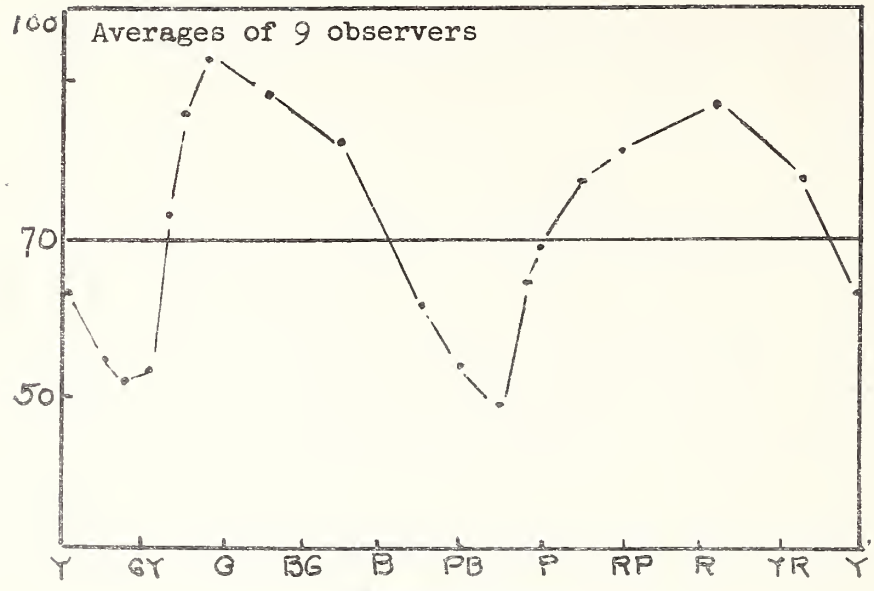

Figure 1.--Appraisals for color rendition of 18 Munsell samples under a DeLuxe Warm White fluorescent lamp on a scale in which the color under an incandescent lamp is rated at 100, and under a Standard Warm White fluorescent is rated at 50.

The choice of test objects for further study was thereupon narrowed down for the present to the 18 papers used in the Barr, Clark, and Hessler studies, with the possibility of cutting this number to 10 if the computational work became too heavy. (Fortunately, through Mr. Ralph Evans' cooperation, we were able to carry through on all of the later work without reducing the number below 18.)

5. WHAT SOURCE SHOULD BE USED AS A STANDARD AGAINST WHICH TO CHECK THE COLOR RENDITION OF THE TEST SOURCE?

It was agreed that the standard source should have a continuous, reasonably smooth, spectroradiometric curve and should differ no more in chromaticity from the test source than some small number of minimum perceptible differences yet to be decided. For adoption as standard, applicable to sources meeting the above chromaticity limitation, it was decided to consider one of the following one-dimensional series of sources:

A. The sources defined by the Planck radiation law.

B. Series A up to a color temperature of 3000K, sources of higher correlated color temperature to be produced by combining a gas-filled incandescent lamp at 3000K with filters of Corning Daylite glass.

C. Series A up to 3000K, additive mixtures of light from an incandescent lamp at 3000K with sun outside the earth's atmosphere with scattering from this source in accord with the inverse fourth-power law (as described by K. S. Gibson in J.O.S.A., 1940).

Series A has the advantage of being maximally smooth and of having a convenient and precise definition; Series B has the advantage of being maximally duplicable for laboratory studies (the only one with which a visual check can be made); and Series C has the advantage of duplicating more closely than Series A or B the spectral energy distribution of the various phases of daylight.

An assessment of the color rendering of the DeLuxe type of lamp relative to the standard type of the same kind by means of the three series of standard distributions A, B, and C was made for the subcommittee by C. W. Jerome by computing the average difference between lamp and standard in percent radiant energy within the eight British bands as recommended by Jerome and Judd (May 1953, Illuminating Engineering, 48, 259) and also by the longer duplication-index method used by them. Results showed that it made little difference by either method which of the three sets of standards was used. For validation studies Series B will be used.

6. IF A ONE-NUMBER APPROXIMATE RATING IS DESIRED, ON WHAT BASIS SHOULD THIS NUMBER BE DERIVED?

It was decided that the approximate rating should be derived in accord with some combination of hue rendition, saturation rendition, and lightness rendition of the test object colors found to correlate with subjective judgments to be obtained as a result of this subcommittee's program. If an abbreviated method, as by use of 5 to 10 spectral bands can be formulated in such a way as to provide this correlation, this would be preferable to a longer method involving computations of the color coordinates of test objects.

7. WHAT SORT OF PROGRAM OF STUDY SHOULD BE ESTABLISHED?

It was agreed that the series of Munsell papers used by Barr and his associates would be computed to see whether actual appraisals can be predicted from the spectral reflectances of the test object and the spectral energy distributions of triplets of sources (standard, Standard fluorescent, and DeLuxe fluorescent). It was agreed that computations would be made for such a triplet at the chromaticities of the Warm White, of the Cool White, and of the daylight fluorescent lamps, and for such other sources as might be useful for this study. (Altogether 12 sources, 6 fluorescent, 3 Gibson, and 3 Corning standards, were used.) It was agreed that validation would consist of a hue rating, a saturation rating, and a composite hue and saturation rating on each of the three triplets of sources (3000K, 4500K, and 6500K), with observations to be made by the simultaneous method, in which

there is no time interval between viewing under the three sources. It was agreed that visual appraisals should be made by the subcommittee, perhaps in a 2-day session, of the color rendering of the series of Munsell papers under the three triplets of lamps as outlined above.

This decision that the subcommittee would itself make the appraisals was made after considerable discussion of assigning the work, perhaps through the help of the Research Fund, to some laboratory where trained personnel might carry on the appraisals under the subcommittee's general direction. But after the preliminary appraisal session, subcommittee members were convinced not only that they could make the appraisals in an adequate manner but that they would learn far more about the problem, and a practical method of answering it, by doing the job themselves.

Once appraisals were made, a method should be derived for computing a duplication index based on spectral reflectance of the selected test objects and sources. To be acceptable this method would have to be shown to yield satisfactory correlation with visual appraisal.

Finally, there should be derived a shortcut method, perhaps involving the eight British spectral bands, yielding nearly as good correlation.

These seven items have provided the basis for the activities of your subcommittee. We have held six all-day sessions of the full group since the beginning of the work, and have assembled a mass of data, both computed and observed, that has required a very great deal of concentrated work between sessions by several members of the subcommittee.

A discussion of the work in chronological order provides a simple method of presentation, and this I shall follow.

Our first meeting, at which the general program was developed, was followed by a session at Nela Park for preliminary observations of samples under specified lamps. This was necessary in order to obtain data on a basis of which we could decide on specific details of the program. The third meeting was called to consider the statistical analysis of these observations, and to make necessary decisions regarding specific details of the program. As discussed under items 4 and 5, the subcommittee decided to use 18 Munsell papers as test objects, and to compute and observe them under three triplets of lamps, each triplet adjusted as closely as possible to the same color, one triplet at about 3000K, one at 4500K, and one at 6500K. For the standard, Series B was to be computed for use in validation, and Series C for the formal standard. For the Warm White fluorescent lamps Mr. Barr had made special lamps, adjusted so that they would color-match an incandescent lamp at 3000K. Lamps were necessary also for 4500K and 6500K, in both Standard and DeLuxe fluorescent. The former were supplied by Mr. Barr, and the latter

by Mr. Jerome, with Corning filters for adjusting 3000K incandescent to 4500K and 6500K supplied by Mr. Macbeth, with the cooperation of A. J. Werner of Corning Glass Works. In addition Mr. Jerome determined, and reported in detail, the spectral energy distribution of hypothetical DeLuxe and Standard fluorescent lamps which would have coordinates on the C.I.E. mixture diagram of black body radiators at 3000K, 4500K, and 6500K, and similar distributions for each of the possible standard series of sources discussed at our meetings. This was done because the usual type of measured fluorescent lamp could not be expected to correspond exactly to the chromaticity of the standards at a fixed color temperature. In fact, even the specially made or selected lamps to be used in this study would require that slight alterations be arbitrarily introduced into the measured spectral distribution curves to correct for this lack of chromaticity duplication of the standard. If this adjustment were not made it might unduly penalize the fluorescent lamps.

Prior to the next meeting, colorimetric computations were made for 18 Munsell papers under 4 sources at 3000K, under 5 sources at 4500K, and under 5 sources at 6500K, and the resulting data reduced to plots on C.I.E. diagrams for each of the three groups of lamps.

Then came our fourth meeting, January 1954 at Nela Park, where eight subcommittee members and five visitors, who contributed substantially to the work of the session, made observations of the color rendition of each of 18 samples under a triplet of lamps, first at 3000K, then at 4500K and at 6500K, with repeat observations for 3000K. A white specimen was included in each series of observations so that each observer could indicate how well the lamps had been adjusted to equality of chromaticity for his own vision. The observations consisted of chromaticness ratings, hue ratings, and saturation ratings made by the simultaneous method agreed upon by the subcommittee. A 4' square box with baffles along the diagonals provided four triangular prism-shaped compartments. The three sources were installed in three of these compartments, adjusted to give equal illumination. The fourth compartment was left dark. Each of the 18 Munsell samples, about 8" x 10", was centered in turn at the back of the box so that a portion appeared in each of the four compartments. The standard source was used in the righthand compartment, the Standard fluorescent in the upper and the DeLuxe fluorescent in the lower one. The color rendition of each sample under the standard source was rated at 100, under the Standard fluorescent at 50, and the observer then rated its appearance under DeLuxe fluorescent in relation to the other two. Figure 2 shows a schematic sketch of the box which was placed at the end of a long table, around which the observers sat with recording sheets on which they indicated their ratings as each judgment was called for. Room lighting was adjusted to the approximate color of the test lamps.

A summary and details of the observations are provided in 23 tables included in the report of this meeting. Included also are measurements of spectral distributions of the lamps used in the tests. These differ somewhat from the data adjusted for use in the computations, which immediately raised a question as to whether the lengthy computations might have to be redone. The summary data of the observations are provided in table 1.

Table 1.--Summary of color rendition ratings by 12-13 observers (I.E.S. Subcommittee on Color Rendition 1/22/54) on a hue circuit of 18 Munsell samples viewed under three lamps of the same color but different spectral energy distributions at 3000K, 4500K, and 6500K. Ratings are reported for chromaticness, hue, and saturation. In each series, results for one lamp are reported relative to results under the other two lamps.

Samples observed		Chromaticness			Hue						Saturation					
								Direction						Direction		
								(2-1)		(3-1)				(2-1)		(3-1)
No.	Munsell Notation	R_1	R_2	S	R_1	R_2	S	1st	2nd	1st 2nd	R_1	R_2	S	1st	2nd	1st 2nd
							3000K									
1	5 Y 6/4	59	60	8	63	64	8	++	++	++ ++	79	71	5	++	0	++ 0
2	10 Y 6/6	48	55	6	52	51	6	++	++	++ ++	65	62	5	++	+	++ +
3	2.5 GY 6/6	41	43	4	22	37	4	+	+	++ ++	37	53	3	+	++	++ +
4	5 GY 6/8	46	45	4	38	48	2	0	-	++ ++	32	44	3	+	+	++ ++
5	7.5 GY 6/6	69	65	5	72	71	5	--	--	0 0	51	51	4	+	0	++ ++
6	10 GY 6/6	81	78	7	76	82	7	--	--	-- --	83	76	5	--	--	0 0
7	2.5 G 6/6	78	80	7	75	79	7	--	--	-- --	84	86	6	--	--	0 -
8	10 G 6/4	81	78	8	73	70	6	-	-	-- --	82	86	8	--	--	- -
9	10 BG 6/4	82	83	8	78	83	7	++	++	-- -	84	84	6	--	--	- -
10	10 B 6/4	76	84	7	83	86	7	++	++	- -	68	88	4	0	-	- 0
11	5 PB 6/8	83	81	7	85	82	8	++	++	0 0	88	81	3	++	+	+ +
12	10 PB 6/8	72	68	5	78	68	5	-	--	- --	74	77	4	++	+	+ -
13	2.5 P 6/8	74	73	6	81	75	6	--	--	- --	77	77	4	0	-	- -
14	5 P 6/8	75	77	7	82	76	7	--	--	- --	73	78	4	--	--	-- --
15	10 P 6/8	75	75	8	78	80	8	--	--	-- --	79	73	6	--	--	-- --
16	5 RP 6/6	71	73	7	77	77	5	-	-	0 0	78	73	7	--	--	-- --
17	7.5 R 6/4	71	70	8	80	78	7	+	++	+ +	73	69	7	--	--	-- --
18	7.5 YR 6/4	62	69	8	72	74	7	++	++	++ ++	62	70	5	--	--	-- --
	Average	69	72	7	70	73	6				70	74	5			
							4500K									
1	5 Y 6/4	83			80			++		++	80			0		-
2	10 Y 6/6	74			78			++		++	79			+		-
3	2.5 GY 6/6	49			48			++		++	50			+		++
4	5 GY 6/8	63			73			-		+	70			-		+
5	7.5 GY 6/6	87			85			--		-	82			-		+
6	10 GY 6/6	86			88			--		-	89			--		--
7	2.5 G 6/6	82			79			--		--	85			--		--
8	10 G 6/4	86			77			+		-	86			--		--
9	10 BG 6/4	83			89			++		0	73			--		--
10	10 B 6/4	82			90			++		+	68			-		-
11	5 PB 6/8	79			80			++		++	79			+		0
12	10 PB 6/8	81			76			--		0	80			+		+
13	2.5 P 6/8	80			76			--		+	82			0		0
14	5 P 6/8	80			88			--		-	80			--		0
15	10 P 6/8	87			92			--		--	85			--		-
16	5 RP 6/6	85			94			-		-	87			--		--
17	7.5 R 6/4	86			90			+		+	82			--		--
18	7.5 YR 6/4	83			85			++		+	81			--		--
	Average	80			82						79					

Table 1.--Cont'd.

Samples observed		Chromaticness			Hue				Saturation				
							Direction					Direction	
No.	Munsell Notation	R_1	R_2	S	R_1	R_2	(2-1) 1st	(2-1) 2nd	(3-1) 1st	(3-1) 2nd	R_1	R_2	S	(2-1) 1st	(2-1) 2nd	(3-1) 1st	(3-1) 2nd
							6500K										
1	5 Y 6/4	83		6	95		5	++		0	78		5	--		-	
2	10 Y 6/6	77		3	84		3	++		0	82		3	--		0	
3	2.5 GY 6/6	75		3	83		3	+		0	84		2	-		-	
4	5 GY 6/8	67		2	46		1	0		-	74		1	0		-	
5	7.5 GY 6/6	75		2	78		3	-		-	81		2	--		-	
6	10 GY 6/6	77		3	77		3	--		--	80		4	--		--	
7	2.5 G 6/6	74		4	75		2	-		--	84		4	--		--	
8	10 G 6/4	72		4	78		4	++		0	78		3	--		--	
9	10 BG 6/4	76		5	84		4	++		++	80		2	-		--	
10	10 B 6/4	78		5	81		5	++		++	76		3	++		--	
11	5 PB 6/8	79		4	82		5	++		++	87		3	++		-	
12	10 PB 6/8	75		3	80		3	-		+	81		2	++		+	
13	2.5 P 6/8	80		4	88		3	--		0	91		2	+		0	
14	5 P 6/8	83		4	89		4	--		+	84		2	0		0	
15	10 P 6/8	81		3	92		4	--		0	92		3	-		0	
16	5 RP 6/6	87		2	91		3	--		0	93		2	-		0	
17	7.5 R 6/4	83		4	86		2	+		0	93		3	--		0	
18	7.5 YR 6/4	79		3	88		3	+		-	87		3	--		+	
	Average	78		4	84		3				83		3				

R_1 and 1st=1st observation
R_2 and 2nd=2nd observation
100 = rating under STANDARD (tungsten lamp at 3000K)
50 = rating under STANDARD fluorescent

Size(S): 0=0
3=small
6=moderate
9=long

Direction: Hue:
Clockwise (RYGBP)= +
Reverse sense = -

Direction: Saturation:
Increase = +
Decrease = -
(2-1) = Std. Flu. minus Std. lamp
(3-1) = DeLuxe Flu. minus Std. lamp

After the data were plotted--observations against computed results--the subcommittee held its fifth meeting and in detail went over all of the 54 source-sample combinations. Many seemed to show good correlation between visual estimates and vectors shown on the chromaticity diagram by computations, most of them showed discrepancies small enough to be not certainly significant, but perhaps 10 percent of the source-sample combinations for the Warm and Cool White fluorescent revealed flat contradictions, particularly for the purples. It was thought that this could be caused by the differences between actual lamps and the data used that had been computed with adjustments for centering. It was decided therefore that the lamps should

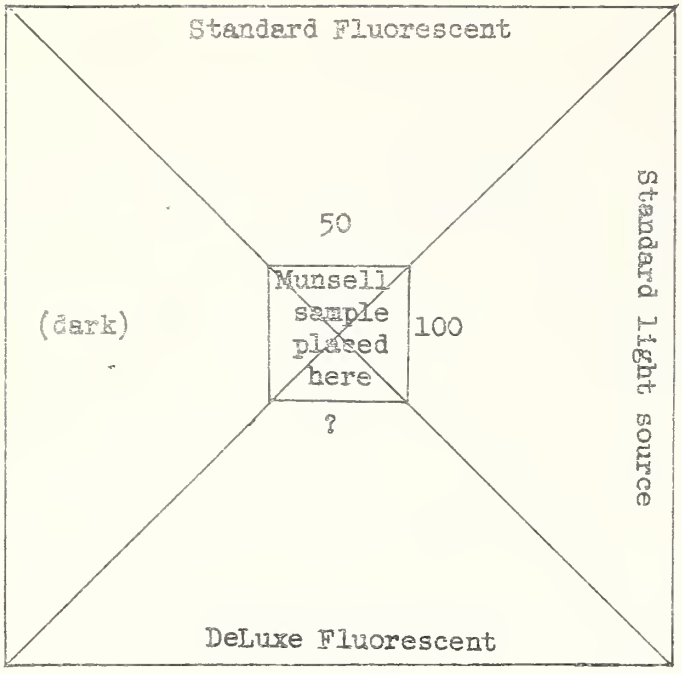

Figure 2.--Box, about 4' on a side, with diagonal baffles dividing it into four compartments, each of which can be illuminated by a different light source. Samples can be illuminated by all sources at one time.

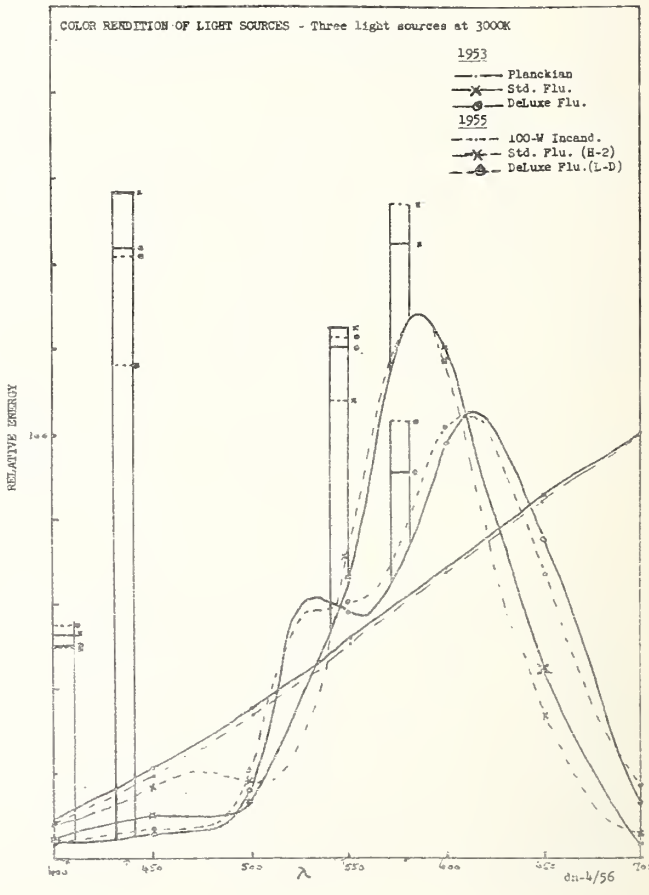

Figure 3.--Spectral energy distributions of 1953 data (adjusted) and 1955 (measured) for three light sources at 3000K.

be remeasured, and the colorimetric data recomputed for the 18 samples. But although this was done, the results failed to account for the discrepancies, as may be seen from the next two figures in which are shown first, in figure 3, curves for the sources at 3000K, the heavy line indicating the data used in the 1953 computations, and the dotted lines indicating those used for the 1955 computations. As may be seen, there is a difference, but on the whole pairs do not look different enough to account for the contradictions found. In figure 4 colorimetric data based on the two sets of data are plotted, the solid lines connecting data for the 1953 computations, and the dotted lines those for 1955. Again, there are differences, but none that account for the reversals shown by observation. Although the remeasurements differ by rather sizable amounts from the first measurements, the contradictions between observation and computation by way of the 1931 C.I.E. Standard Observer remain essentially unchanged.

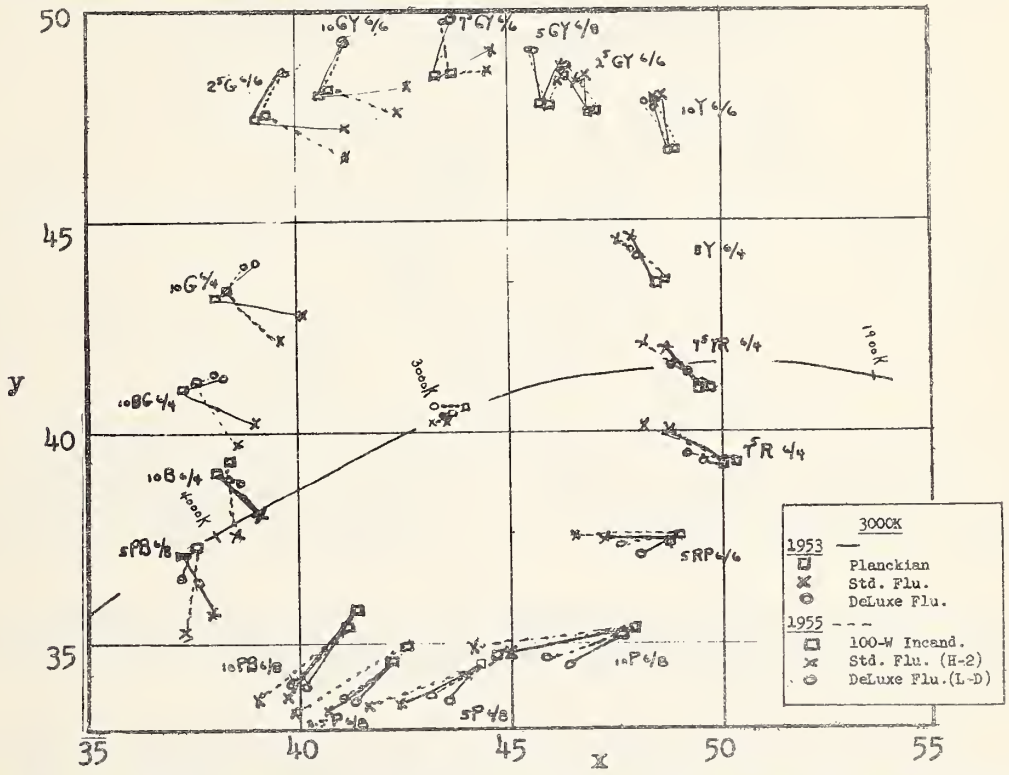

Figure 4.--C.I.E. colorimetric data for 18 Munsell samples under light sources at 3000K for which energy distributions are shown in previous figure.

Similar data for the 4500K and 6500K results are shown in figures 5 to 8. But, as may be seen, these differences are less than those for 3000K.

The next step was to hold a session (our sixth) in which the source-sample combinations yielding the biggest discrepancies were again set up for observation in an effort to track down the cause of the discrepancies. Observations repeated on the 2.5P and 5P samples, for which the contradictions

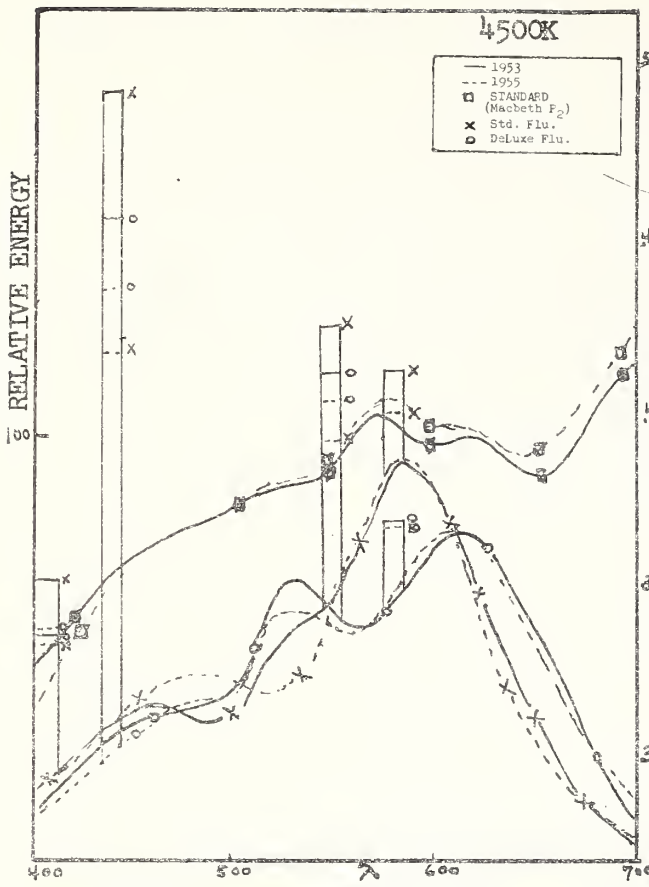

Figure 5.--Relative spectral energy data for 3 sources at 4500K.

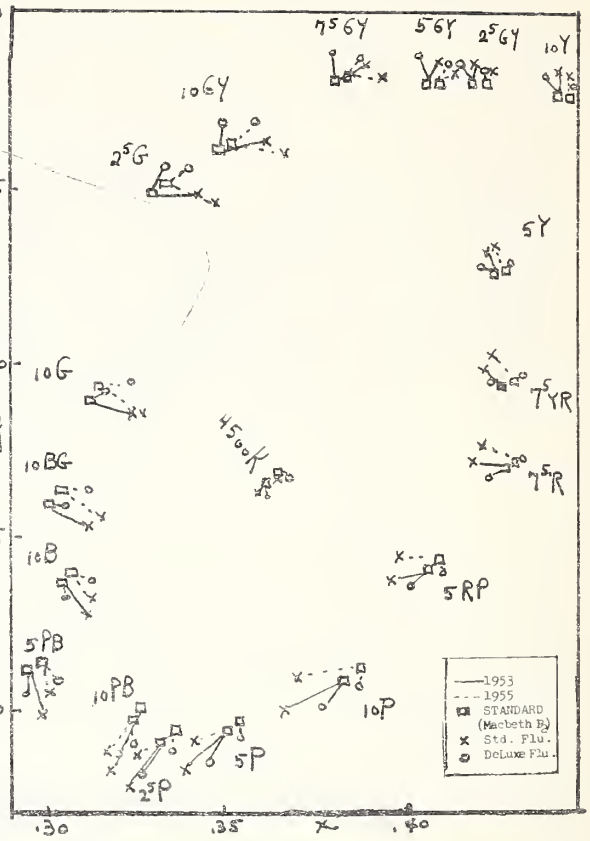

Figure 6.--Colorimetric data for 18 samples under 4500K sources.

were most definite, corroborated those made in January 1954, that the fluorescent lamps render the colors of these samples bluer and less saturated than the rendition of them by the incandescent source.

Three sources of error must be considered: The spectral energy distribution of the source, the spectral reflectance of the sample, and the color-mixture functions of the observer. In regard to the first, after comparing measurements of the spectral energy distributions of the lamps made in two laboratories, and after reviewing the very substantial progress toward accounting for and eliminating their disagreements, it appeared reasonable to the subcommittee to assume that results of the lamp measurements are essentially correct. In regard to the second possible source of error, the spectral reflectance measurements of the samples, these show fairly smooth curves that in no way appear to be the cause of our contradictory results. Curves for these samples, including the 2.5P and 5P, are shown in figure 9. (Note: Perhaps we should look again at these curves, particularly in relation to the peaks of the fluorescent lines at wave length 436 mμ.)

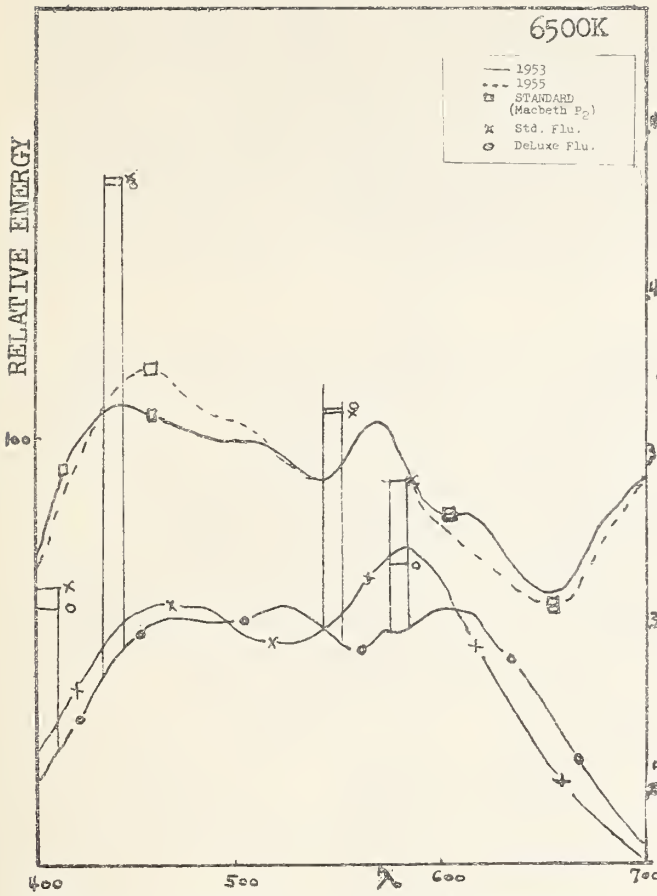

Figure 7.--Relative spectral energy data for 3 sources at 6500K.

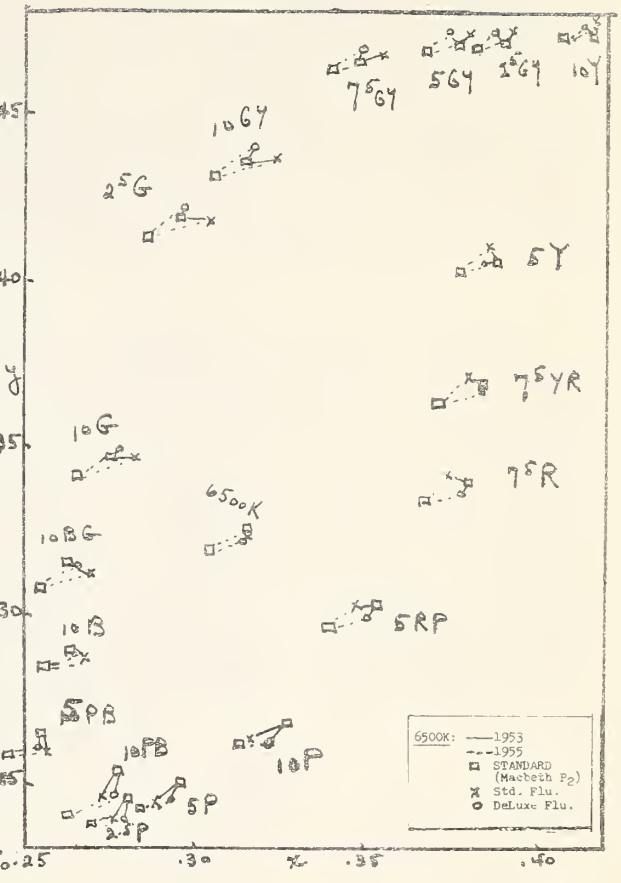

Figure 8.--Colorimetric data for 18 samples under 6500K sources.

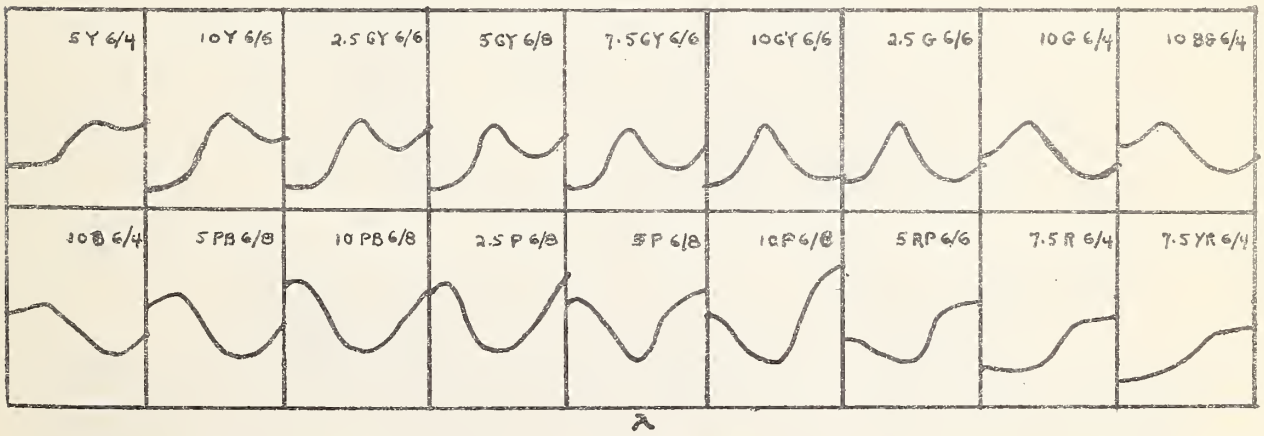

Figure 9.--Distribution of spectral reflectance properties of the 18 Munsell samples used in these tests.

At any rate, the importance of the third possible source of error was established by making observations at a distance of 20 feet (angular subtense about 2°) and at 2 feet (angular subtense about 20°). It was found that at 20 feet all observers found the saturation for the 2.5P sample to be less under the fluorescent lamps than under incandescent, while at 2 feet this was reversed, and the saturation was greater under the fluorescent than under the incandescent. This led the subcommittee to make comparisons of the source-sample combinations found by computation to be near matches. The results of these comparisons seemed encouraging, and indicate that the determination of spectral energy distributions of the fluorescent sources is generally reliable.

Because of the difference in observations at different angular subtense, we thought we really might have the answer. Therefore it was agreed that source-sample combinations should be recomputed for the 2.5P and 5P samples at 3000K by means of the color-mixture functions newly found for 2° and 10° fields by Stiles of the National Physical Laboratory. The Stiles data became available only in late February, and in March these computations were made for the purple samples by C. W. Jerome. The results are shown in figure 10. As far as can be seen, this does not supply our answer, for the samples calculated for the fluorescent lamps seem even more saturated--as I believe you can see, for they are farther from the source--than those for the tungsten lamps when calculated for the Stiles observers, both 2° and 10°, than for the C.I.E. Standard Observer. So this was not our answer!

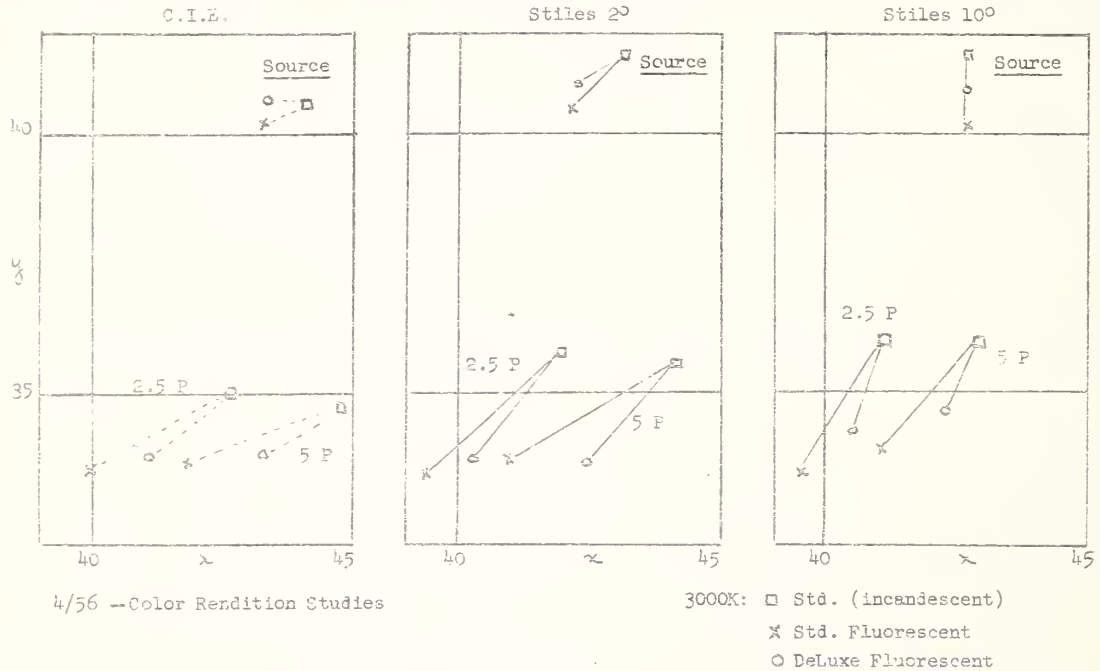

Figure 10.--Colorimetric data plotted on (x,y)-diagrams for three sources at 3000K and for two purple samples seen under those sources by three different observers, the C.I.E. Standard Observer, an observer based on Stiles 2° data, and an observer based on Stiles 10° data.

While these data were being computed, a uniform lateral transformation of all the chromaticity points to correct for the differences noted by observation in the light sources was made by Mr. Clark for an RUCS (rectilinear-uniform-chromaticity scale) diagram. The result is shown for the 3000K series in figure 11. For the 2.5P color it cannot be said that this RUCS transformation provides a solution, nor does the saturation seem less under fluorescent than under tungsten for the 5P 6/8, although this diagram does seem to improve its relative position as compared to the C.I.E. diagram.

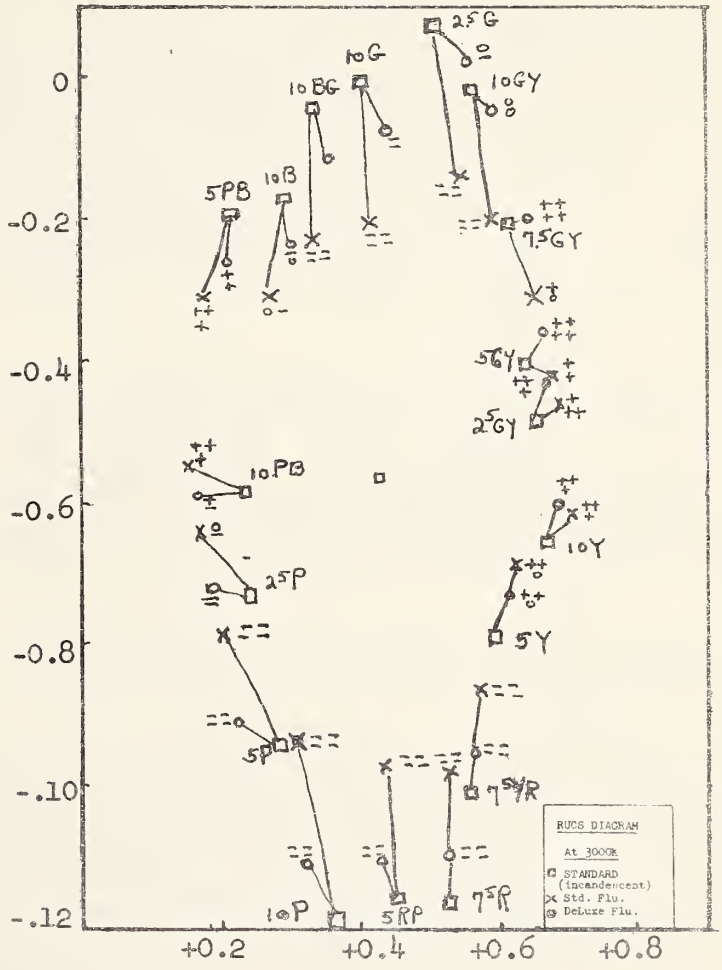

Figure 11.--Colorimetric data for 18 Munsell samples on RUCS diagram. Observed direction of saturation from STANDARD: increase indicated by +, decrease by -.

What we need--as we have known and have long been trying in these and other ways to get--is a plot of equally spaced loci of hue and saturation for other sources such as we have had for C.I.E. Source C in the Munsell renotation diagrams for hue and chroma loci at different value levels. Based on measurements of a basic series of Munsell color samples computed for nine sources (Nickerson-Wilson, Illuminating Engineering, 45, 507-517, 1950), the diagrams in figure 12 have been prepared in USDA laboratories for 3000K, 4500K, and 6500K, for the 6/ value level in which we are interested. For the 3000K conversion, data available for these Munsell samples at C.I.E. Source A were used as a basis, and corrections made for the smoothed renotation lines by allowing for the same relative amount of difference from the smoothed lines as was found necessary in smoothing for the Source C data. The same general procedure was followed in preparing a 4500K diagram, using the data for the Munsell samples available for Cool White fluorescent (about 4500K). This was done to provide a smooth network of lines (based on the hue and chroma lines for Source C) to which one might refer in judging the direction of differences obtained in our subcommittee tests; there was no expectation that the element of "equal spacing," which makes the data so important for Source C, would carry over into the diagrams thus prepared for illuminant chromaticities other than C.

I should like to note here, however, that it has long been my own feeling that the hue and chroma loci on such diagrams could be corrected to give equal spacing if a large scale set of observations under C.I.E. Sources A and B were provided for this purpose. It would mean extensive observations such as were required for smoothing the Munsell data for daylight conditions --a long, but not impossible job, for which the necessary computations already have been published for this very purpose in the Nickerson-Wilson paper.

To get back: What we need is a diagram of visually equally spaced loci of hue and saturation for standard light sources at the 3000K, 4500K, and 6500K levels with which our studies are concerned.

If the studies of Helson, Judd, and Warren now being carried forward with I.E.S. Research Fund support are essentially correct, we should be able by means of the vonKries coefficient law to deduce the loci of chromaticities yielding color perceptions of constant hue and saturation for an observer adapted to another source. This conversion we have made by using the type of formula discussed by Wyszecki in 1954 (J.O.S.A., 44, 787-792), transforming the loci of Munsell hue and saturation from daylight adaptation to adaptation under incandescent illumination at 3000K, assuming adaptation to a neutral surround color, as was used in the observations. The resulting diagram, covering the range of the 18 colors with which this study is most immediately concerned, is shown in figure 13. It looks not too different from the 3000K plot in figure 12, perhaps with more difference for hue than for saturation, and a slight shift in direction of the long axis. However, even this transformation does not help to resolve our problem, for according to this diagram the 2.5P and 5P samples still plot as more saturated for fluorescent than for tungsten light, while the observations on these samples

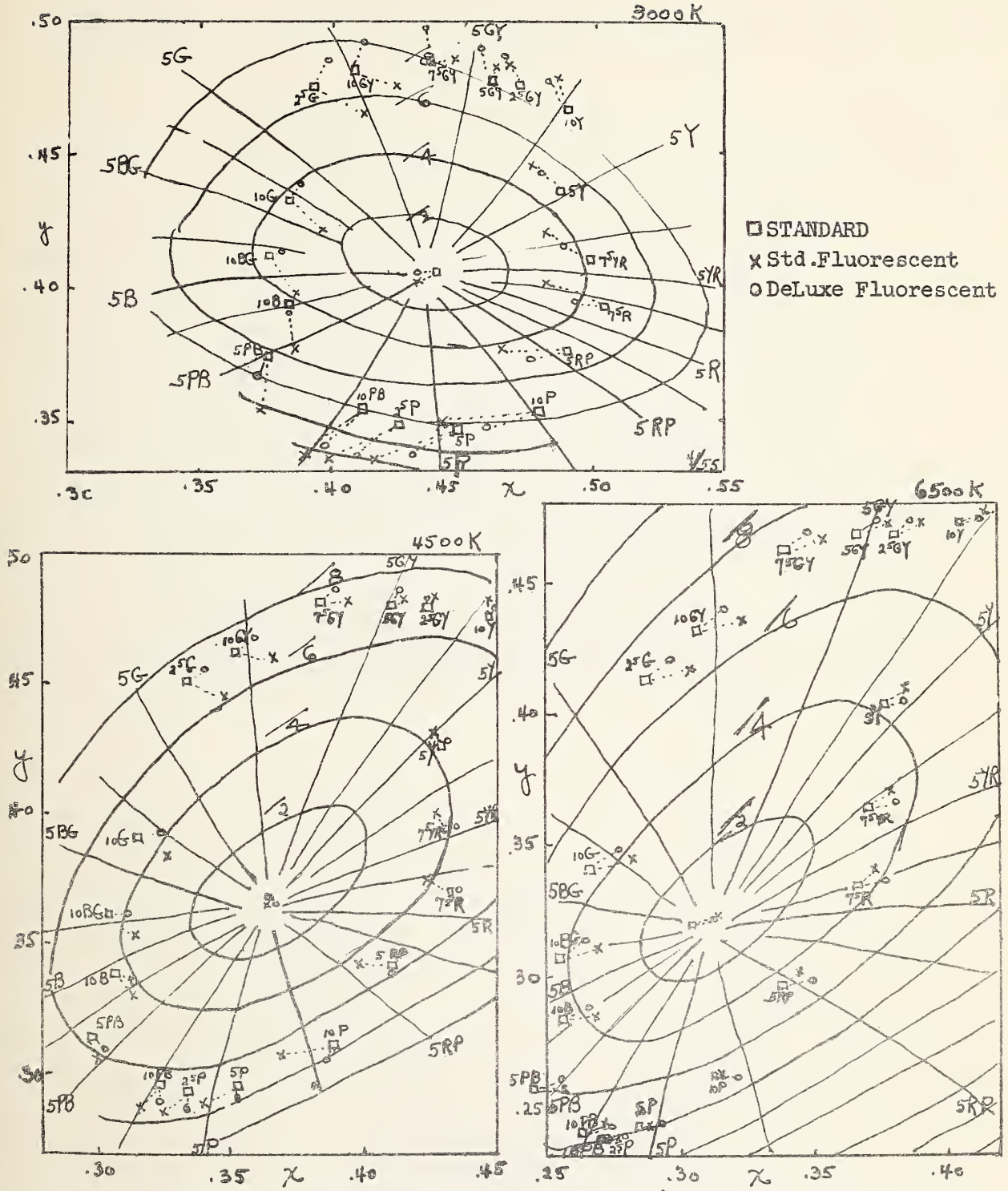

Figure 12.--Smoothed lines of Munsell renotation (for observations in daylight) transferred so they will be centered on other sources (3000K, 4500K, and 6500K) for which, or near which, Munsell papers are measured.

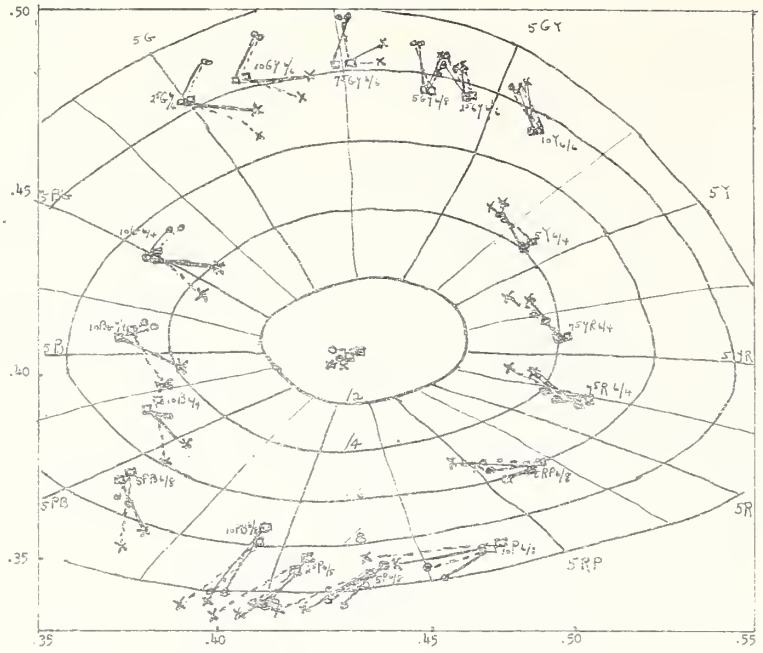

Figure 13.--Munsell renotation loci for 6/ value transformed from C.I.E. Source C to 3000K according to Nelson, Judd, and Warren.

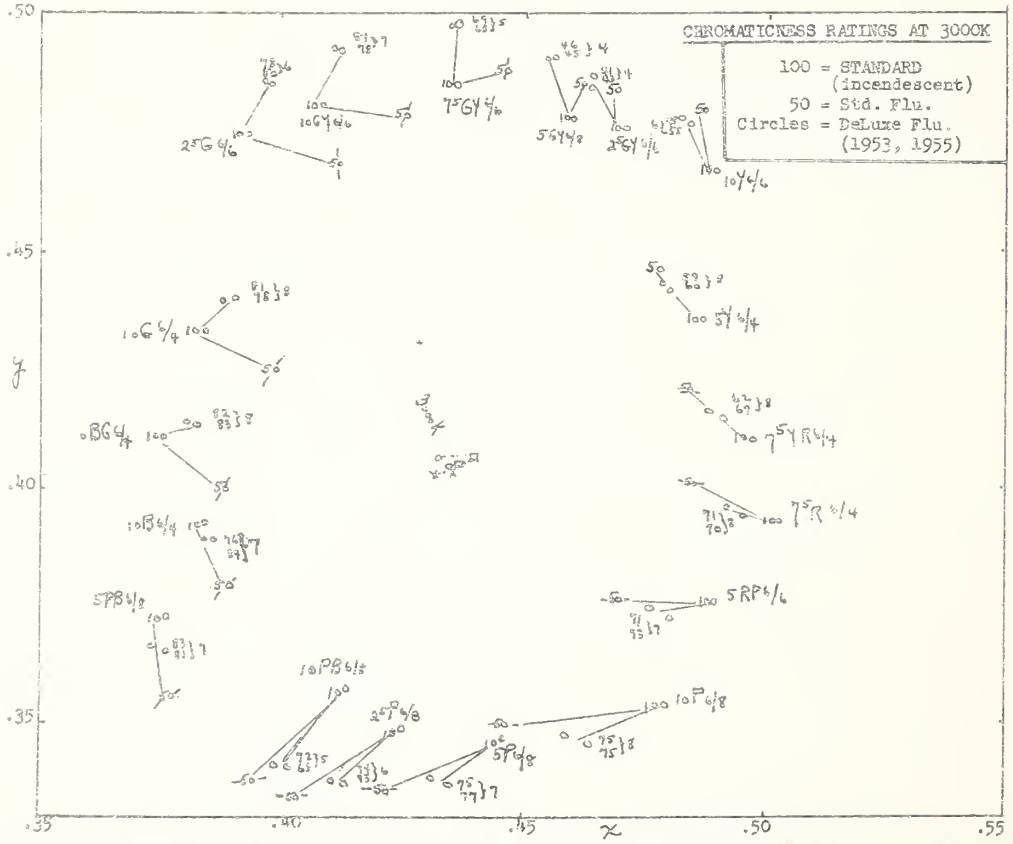

Figure 14.--CHROMATICNESS ratings: 18 Munsell samples under DeLuxe fluorescent.

say they are less saturated under light from the fluorescent lamps. (This may mean that there was a change in adaptation depending on the color in the central field, and that adaptation to a neutral surround is not the answer.)

It looks as if what we need, in order to fit observations with computed data, is a diagram with a sharp upward curvature for saturation loci. Figures 14 to 16 have been prepared to help study in detail what is needed. Each figure shows the position of the computed data for 3000K plotted on C.I.E. (x,y)-diagrams. On figure 14, these are accompanied by the average ratings for chromaticness obtained for two independent sets of observations. The rating for color rendition of samples under the incandescent lamp is "100," under the Standard fluorescent, "50." The position of the 1953 and 1955 computations for each color under incandescent is indicated by the position of the numbers 100 and 50. Where the spread between 1953 and 1955 data is more than that covered by the number, the range is indicated by short lines extending through these numbers. Separate circles for the two sets of data are indicated for the DeLuxe fluorescent results. Ratings under the DeLuxe lamp are given for two observations. The relative size of the differences are noted by the accompanying number, 0 to 9, in which 0 represents "no difference" and 9 represents a "large" difference. Hue observations are shown in figure 15, and those for saturation in figure 16. The observed

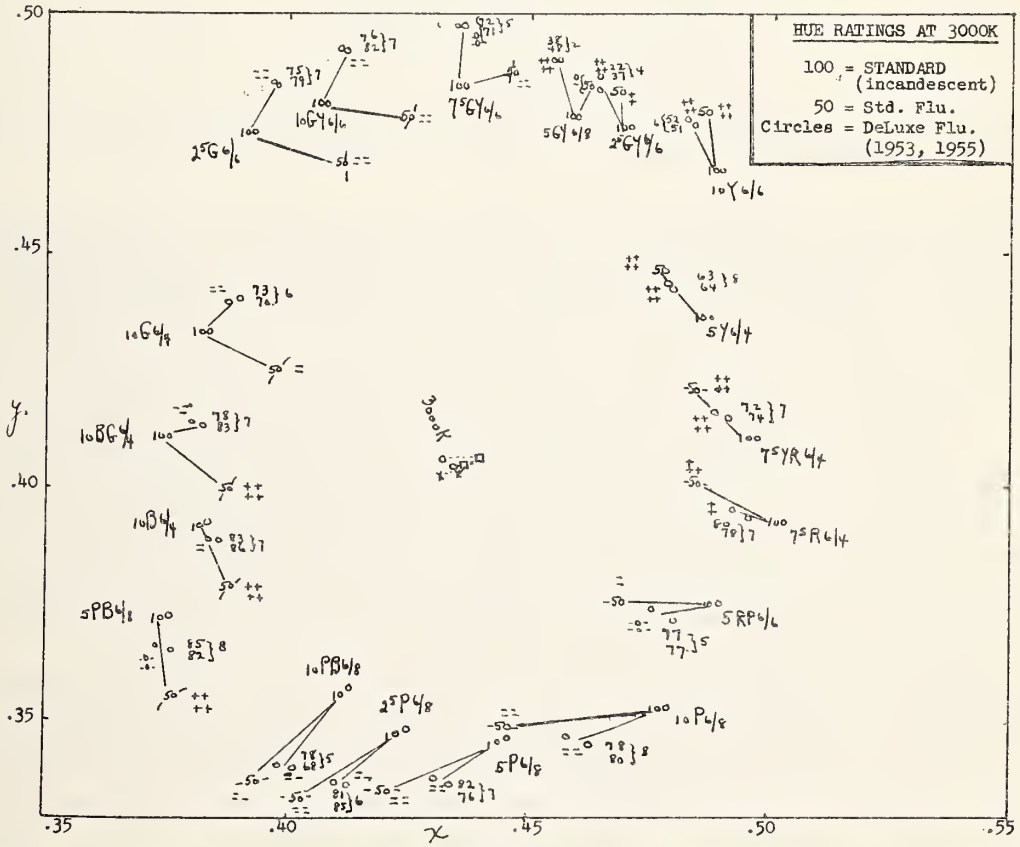

Figure 15.--HUE ratings: 18 Munsell samples under DeLuxe fluorescent.

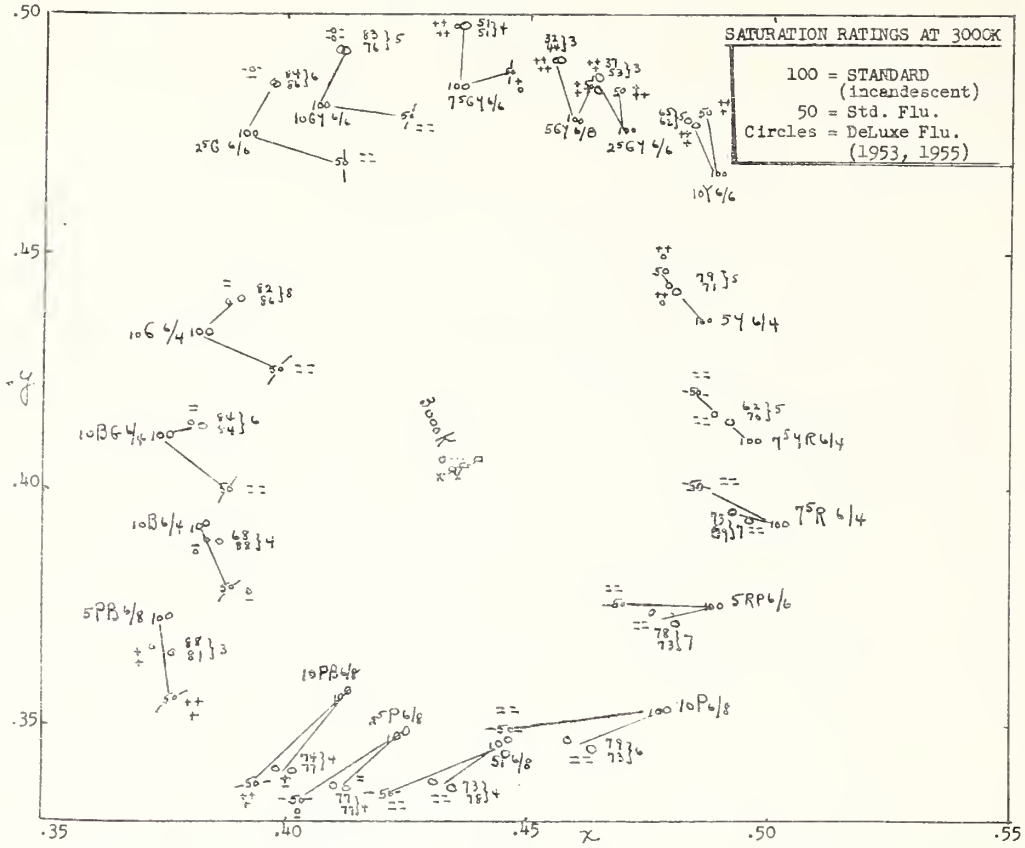

Figure 16.--SATURATION ratings: 18 Munsell samples under DeLuxe fluorescent.

direction of hue change from the STANDARD (at 100) in a clockwise direction, R-Y-G-B-P, is indicated by +; in the opposite sense by - . The observed direction of increase in saturation is indicated by +; decrease by - . The diagrams are needed in order to assess the relative degree of agreement of observed and calculated results. As may be noted, the direction of change is not always the same for the color under the two fluorescent lamps as compared to the color under the tungsten lamp. Therefore the observations regarding direction of change for the color under each of the fluorescent lamps, as compared to the color under the incandescent lamp, have been included in figures 15 and 16. A preliminary attempt has been made to draw in lines that would represent the shape needed to bring computations and observations into agreement. The shape needed for saturation, based on such thinking as has been described, is shown in its present preliminary state in figure 17.

Whether this last path will lead to a successful answer to our problem is something I hesitate to predict. If it does, then it will also lead to a considerable revision of much of our thinking in regard to methods of finding loci of equal hue and saturation for a standard observer under different chromaticities of light sources, even when confined to a series that may be considered as standard (as the A, B, C series discussed earlier under Question 5). Much greater attention may have to be paid to the importance of the observing conditions than we have supposed up to now.

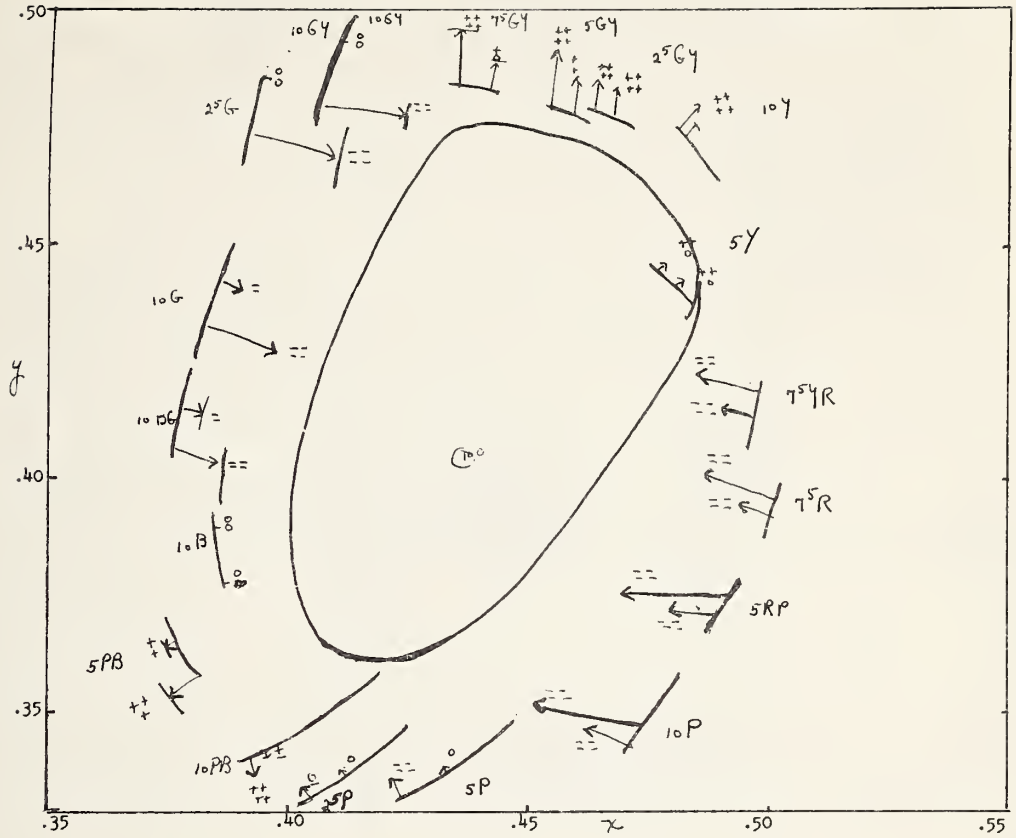

Figure 17.--Preliminary attempt to describe shape of saturation loci necessary to bring into agreement computations and observations for saturation for 18 Munsell samples under three lamps at 3000K.

To bring the matter up to such a point and leave you may seem to some of this audience rather pointless. But to others of you I hope this discussion may have given you some insight into the magnitude of the problem, and the fact that we are exploring new territory. Colorimetry is a science that has only begun to be applied to colors viewed under a variety of light sources. In making these applications we find we must push back the frontiers. In this present study we have been trying out several paths that have been indicated, but not previously followed. These we must follow until we find one or more that leads to a sound and complete answer. One other very practical consideration that I have had in mind in preparing a report for this meeting is that it provided an urgent reason for reviewing and summarising what has been done to date, so that others beside our subcommittee members who are interested in this problem may have a report of our work to date.

As soon as copies of this report are available--complete with these and other diagrams--they will be provided to our subcommittee members, together with details relating to much of the later discussions. Our next meeting will be called to study in detail the observations in relation to the computed data. There is no question but that there is an answer; it is my hope that we shall be able soon to find it. No rating for color rendition will be completely satisfactory until we have a good correlation between observation and computation.

In this report no mention has been made of many other lines of discussion regarding color rendition that have come up in our subcommittee meetings--e.g., the subject of preferences for colors, and whether weights should be given to colors that change toward a preferred color, as against an equal size of difference but in the direction of a disliked color--as butter, which can be a yellow toward red, but not toward green.

These, as well as other related matters, will be considered before your subcommittee reaches its goal of reccmmending "a method of measuring and specifying the color rendition properties of light sources."